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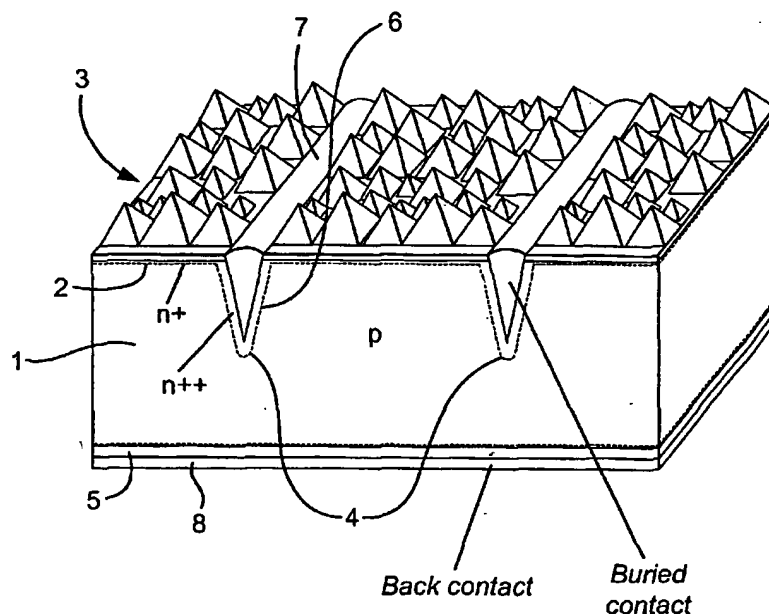
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(54) Title: PROCESS FOR MANUFACTURING A SOLAR CELL



(57) Abstract: A process is disclosed for incorporating a back surface field into a silicon solar cell, which comprises the steps of:  
a) depositing a layer of aluminium on the rear surface of the cell; b) sintering the aluminium layer at a temperature of between 700 and 1000°C; c) exposing the cell to an atmosphere of a compound of a Group V element and diffusing at a temperature of between 950 and 1000°C, so as to dope exposed p-type silicon surfaces with said Group V element, preferably phosphorus.

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### PROCESS FOR MANUFACTURING A SOLAR CELL

The present invention relates to p-n junction solar cells, and more particularly to processes for fabricating them.

Photovoltaic cells made with silicon wafers for terrestrial applications usually comprise a p-type silicon wafer. One surface of the wafer is "doped" (usually with phosphorus at temperatures of 900-1000°C) to make it n-type and produce the basic p-n junction which is the active component of the solar cell. Metal contacts are then applied to the front and rear surfaces (the n and p surfaces) to enable the photo-generated current to be carried from the cell. In the case of the front contact the metal is typically deposited as an open grid pattern to allow light to be absorbed by the exposed silicon surface. The front grid can be deposited in embedded grooves to reduce grid shading losses. This type of solar cell is often known as a *Buried Contact* solar cell (also referred to as a *Laser Grooved Buried Grid* - LGBG solar cell). The basic cell is disclosed in EP 156366A.

The process for fabricating such a cell typically includes the following initial steps:

- 1) in the case of monocrystalline silicon wafers with [100] crystal orientation, etching of the silicon surface in a caustic solution to form random pyramids;
- 2) doping the top surface of a p-type silicon wafer with a Group V element, typically phosphorus, to produce the n<sup>+</sup> layer;
- 3) adding a top surface coating of silicon nitride, to act as an antireflection layer and also as a dielectric (non-conducting) layer in order to prevent metal plating on unwanted regions of the top surface;

4) cutting grooves into the surface of the wafer into which metal will be plated. The grooves are typically cut using a laser but may be chemically etched, plasma etched, or mechanically formed using a diamond saw;

5) doping the exposed p-type silicon surface in the grooves n-type with a Group V element, typically phosphorus;

6) treating the cell to provide a back surface field (BSF), by doping the rear surface with an electron "acceptor" such as aluminium or boron;

7) plating metal contacts into the grooves to provide an electrically conducting front contact, and also simultaneously into the rear surface in order to provide an electrically conducting back contact.

Following the above steps, it is necessary to electrically isolate the edges of the wafer. This step is not relevant to the present invention.

A back surface field (step 6) on a crystalline silicon solar cell serves to boost the efficiency of the cell by repelling photo-generated minority charge carriers (electrons in p-type silicon) away from the rear surface where they would otherwise recombine with majority carriers (holes in p-type silicon) before they can be made to do useful work in an external circuit. In high efficiency laboratory cells the BSF is often formed by depositing a film of aluminium by physical vapour deposition and heating to temperatures in excess of 1050°C (typically over 1100°C). However, these cells typically achieve a BSF due to special circumstances which are not appropriate for low-cost commercial cell fabrication:

- The aluminium thickness used is typically equal to or greater than 2  $\mu\text{m}$  and it has been reported that this is a minimum thickness required for the formation of an effective BSF.
- The silicon wafers used are made by Floating Zone (FZ) melting and contain low concentrations of oxygen. These wafers can be heated to high temperatures for extended periods without destroying their electronic performance. For reasons of economy however, commercial cells must be made from Czochralski (CZ) silicon wafers which contain dissolved oxygen impurities and suffer performance degradation when heated above 1000°C for extended periods.

In commercial solar cells, the BSF is usually formed by printing a thick film (~20 $\mu\text{m}$ ) of aluminium or spin-coating a film of a boron containing compound onto the

rear surface of the silicon wafer, and heating the film to temperatures in the range 800-900°C for aluminium (1000-1100°C for boron), to incorporate the metal at a concentration of about 100 ppm. As a result these cells use a relatively large quantity of aluminium. In cells incorporating a BSF through the use of a thin film (~2µm) aluminium layer, the rear surface of the wafer typically incorporates a thin dielectric layer of silicon oxide or silicon nitride. In addition to passivating the rear surface, this dielectric layer serves as a barrier to prevent phosphorus atoms from doping the rear surface (during formation of the front junction of the cell or the doping of the groove) and preventing good BSF formation. Doping of the aluminium atoms through this layer is achieved by either high temperature diffusion (in the case of silicon oxide barrier) or through the formation of apertures in the dielectric layer to produce a localised BSF. But this adds additional cost and complexity to cell fabrication.

As a result, there is a need for a method of applying a BSF to a silicon solar cell which is more efficient than that used for commercial cells, and which can also lead to improved cell efficiency.

The present invention provides a process for incorporating a back surface field into a silicon solar cell which comprises the steps of:

- a) depositing a layer of aluminium on the rear surface of the cell;
- b) sintering the aluminium layer at a temperature of between 700 and 1000°C;
- c) exposing the cell to an atmosphere of a compound of a Group V element, and diffusing at a temperature of between 950 and 1000°C, so as to dope exposed p-type silicon surfaces with said Group V element.

By subjecting the cell to the Group V element doping after deposition of the aluminium layer, a number of significant advantages are achieved. The absence of the Group V element doping prior to the deposition of the aluminium layer means that the aluminium doping is not compensated by the presence of doped Group V element on the rear surface. Additionally, the requirement for a silicon oxide or silicon nitride coating on the rear surface to prevent doping as mentioned previously is removed, leading to further process economies. Optionally, the sintering step and the subsequent doping step (steps (b) and (c) above) may be combined, leading to further economies in the process. Additionally, this process allows for low-cost CZ wafers to be used whose performance would otherwise be impaired if used in alternative processes employing

sintering temperatures in excess of 1000°C.

The aluminium deposition is performed by evaporative deposition or sputtering. Optionally, the front surface of the wafer may be washed, usually with de-ionised water, subsequent to the aluminium deposition and before the sintering, in order to remove any aluminium dust from the front surface where it is not required. The preferred temperature for the sintering of the deposited aluminium is between 850 and 1000°C, particularly between 900 and 960°C. The duration of the sintering is generally no more than 30 minutes, preferably no more than 10 minutes.

Preferably the Group V element is phosphorus or arsenic; more preferably phosphorus. A typical compound used is  $\text{POCl}_3$  which is oxidized on the wafer surface to  $\text{P}_2\text{O}_5$ . The doping is preferably carried out at a temperature of between 960 and 1000°C. Usually the exposed p-type silicon surfaces are in the grooves cut into the surface of the cell.

The silicon cell may be monocrystalline or polycrystalline (multicrystalline). A specific embodiment of the invention will now be described with reference to the accompanying drawing, which shows in diagrammatical form the structure of a typical Buried Contact solar cell.

Figure 1 shows a silicon wafer 1.

As previously described, the first stage in the fabrication process is to dope the top surface 2 of the wafer with phosphorus to produce an n-type layer (as indicated n+ in the diagram). This is done by exposing only the top surface to  $\text{POCl}_3$  and  $\text{O}_2$  in a quartz tube furnace at about 800-900°C, so as to provide a thin  $\text{P}_2\text{O}_5$  layer on the silicon surface, the phosphorus of which dopes the silicon in a subsequent higher temperature step.

A silicon nitride coating 3 is then applied to the top surface to provide an antireflection layer; this layer also functions as a dielectric (non-conducting) layer to prevent subsequent metal plating on the top surface, and a barrier to further surface doping of phosphorus during the groove doping step. The silicon nitride is deposited in a quartz tube furnace at 800-900°C by low pressure chemical vapour deposition, usually using dichlorosilane and ammonia gases.

Parallel grooves 4 are then scribed into the top surface of the silicon using a laser. The grooves are typically  $20\mu\text{m}$  wide and about  $40\mu\text{m}$  deep, and about 1.5mm apart.

The wafer is then immersed in a caustic etch to dissolve silicon debris from the laser cutting and to etch the groove walls.

Because the grooves cut through the surface layer of n-type doped silicon to the p-type silicon below, it is necessary to re-dope the exposed p-type surface in the grooves with phosphorus. However in accordance with the present invention, an aluminium layer is deposited on the back surface of the wafer before this is done.

Prior to deposition of the aluminium, the back surface of the wafer may be cleaned and etched by plasma etching and/or submerging the wafer in an acid or alkaline bath. A 0.2 – 2.0  $\mu\text{m}$  thick layer of aluminium 5 is then deposited by evaporative deposition, after which the wafer is rinsed in water to remove any aluminium dust from the top surface. Then the wafer is sintered in a quartz tube furnace at 950°C.

Following the sintering of the aluminium layer the wafer is immersed in a dilute (0.5 to 4.0%) solution of hydrofluoric acid to remove any silicon oxide growth in the grooves. The wafer is then rinsed in de-ionised water and dried.

Following oxide removal in the grooves, the wafer is treated with  $\text{POCl}_3$  and  $\text{O}_2$  in a quartz tube furnace at 980°C. This provides a new n-type layer 6 (denoted n++ in the diagram) on the surfaces of the grooves.

In an alternative embodiment, the steps of sintering the aluminium and depositing the new n-type layer 6 in the grooves are combined, with the high temperature of the doping step also serving to sinter the aluminium.

A base layer of electroless nickel is then deposited in the grooves and also on the rear surface of the wafer. Following sintering, further deposition of nickel, copper and silver is carried out in both the grooves and on the rear surface to provide a conductive copper contact 7 in the grooves and an electrically conducting layer 8 on the rear surface. The cell is then completed by edge isolation (laser scribing and cleaving the edges), in a manner well known to those skilled in the art.

Tests have shown that the process of the invention results in a solar cell having an efficiency approximately 6% greater than that achieved by cells of the prior art: thus the overall efficiency of the cell rises from about 16% to about 17%.

### 30 EXAMPLES 1-3

147cm<sup>2</sup> area solar cells were prepared under varying conditions using the following general process.

### Starting Material

Use was made of conventional CZ silicon wafers doped *p*-type with boron to a resistivity of 1.2 ohm.cm and grown with [100] crystal planes parallel to the wafer surface. The wafer dimensions were 127mm square with rounded corners of a diameter  
5 150mm. The wafer thickness was 300 $\mu$ m. Such wafers are commercially available, for example from Bayer Solar GmbH, PV Silicon GmbH or Pillar.

### Wafer Surface Preparation

The wafers were anisotropically "texture" etched in a solution of sodium hydroxide and propanol at a temperature of 90°C and cleaned by subsequent immersions  
10 in hydrofluoric acid and hydrochloric acid with intermediate and final rinsing in de-ionized water followed by drying.

### Phosphorus Doping and Silicon Nitride Deposition

Wafers were placed in pairs (touching) in the slots in a quartz wafer carrier and treated in an atmosphere of POCl<sub>3</sub> vapour and oxygen at a temperature of 800°C to  
15 deposit a 10nm thick film of phosphorus glass on the exterior surfaces. The wafers (in their quartz carrier) were then treated in an atmosphere of silicon nitride and ammonia gases at a pressure of 40 Pa and a temperature between 780 and 860°C to deposit a 110 nm thick film of silicon nitride on the exterior silicon.

### Plasma Etch

20 This is not an essential part of the process but is desirable for good cell results. As a consequence of the previous process, some unwanted silicon nitride is generally deposited around the perimeter of the rear of the wafer (to a distance of 10-20 mm). This film was removed by etching in a gas plasma formed with freon and oxygen. This was achieved by placing the wafers with their front surfaces touching each other and  
25 exposing the rear surfaces to the gas plasma.

### Laser Grooving

A number of grooves were cut into the front surface (the surface with the silicon nitride film) that would subsequently form the conductive grid by which the electrical current is carried. Each groove had dimensions of typically 20 $\mu$ m width and 40 $\mu$ m  
30 depth and was formed by laser ablation of the surface material using a Nd:YAG laser Q-switched at a frequency of 50kHz and traversing the wafer surface with a velocity of 500 mm/s. The groove pattern comprised a first group of parallel lines at a pitch of



1.5mm distributed over the entire surface and a second group of grooves perpendicular to the first group and joined in two bundles with a distance of about 6cm from each other. Each bundle comprised parallel grooves within a width of 1.5mm.

#### Groove Cleaning

- 5        The action of laser grooving generally results in silicon debris on the wafer surface and groove sidewalls that contain undesirable crystal imperfections. Accordingly the wafers were etched in a solution of sodium hydroxide at 50°C to dissolve the silicon debris and etch the groove walls to a depth of a few microns. The wafers were then cleaned by subsequent immersions in hydrofluoric acid and hydrochloric acid with  
10       intermediate and final rinsing in de-ionized water followed by drying.

#### Aluminium Deposition

A film of aluminium of thickness 500nm was deposited on the rear wafer surface by thermal evaporation (sputtering has also been used). The wafers were then rinsed in de-ionized water to remove any aluminium dust, and dried.

#### 15       Aluminium Sintering

- The silicon wafers were placed in a quartz wafer carrier that was inserted into a quartz tube, and heated to the required temperature (see Table 1 below for temperature) for a period of 15 minutes in an oxygen atmosphere. Following the sintering process the wafers were then cleaned by immersions in hydrofluoric acid and hydrochloric acid  
20       with intermediate and final rinsing in de-ionized water followed by drying.

#### Groove Doping

- The silicon wafers were placed in a quartz wafer carrier as pairs (not touching) with the aluminium surfaces facing each other. The carrier was then inserted into a quartz tube and treated in an atmosphere of POCl<sub>3</sub> vapour and oxygen at a temperature  
25       of 960-1000°C for 20 minutes to dope phosphorus into the exposed silicon surface to a sheet resistivity of 8 ohm/square.

#### Nickel Plating

- The wafers were immersed in a solution of 4% hydrofluoric acid for 90 seconds and rinsed in de-ionized water. The wafers were then immersed in an alkaline  
30       electroless nickel plating solution (Enplate A1-100) for 100s to deposit 0.1µm Ni film followed by a rinse in de-ionized water before drying.

### Nickel Sintering

The nickel-plated wafers were heated to a temperature of 400°C for 6 minutes in a nitrogen atmosphere to sinter the nickel into the silicon surface.

### Copper Plating

- 5       Wafers were treated using the following procedure to apply a 5 micron thick film of copper in the grooves and on to the rear surface. A 2 minute immersion in 30% nitric acid was followed by a 10 minute rinse in water, a 30 second immersion in 1% hydrofluoric acid, a 10 minute rinse in water, a 60 second immersion in an acid electroless nickel solution (Enplate Ni-416) at a temperature of 90°C, a 30 second rinse  
10   in water, a 120 minute immersion in electroless copper solution (Enplate Cu-703) at a temperature of 50°C, a 10 minute rinse in water, a 6 minute immersion in a solution of silver potassium cyanide at room temperature, and a 10 minute rinse in water followed by drying.

### Edge Isolation

- 15       The undesired electrically conductive deposits of nickel and copper on the edges were removed by cutting a groove to a depth of 100-150  $\mu\text{m}$  into the silicon surface on the rear of the wafer and around the perimeter at a distance of 1mm from the wafer edge. Cleaving and discarding the 1mm silicon at the edge then removed the edge material. The cell was now complete and ready for testing.
- 20       Table 1 below shows the different conditions employed in the steps relevant to the present invention and the order in which they were carried out, together with measurements indicating the efficiency of the cells obtained.
- 25       Example 1 was carried out according to the prior art method, in that the "Groove Doping" step above was carried out before the "Aluminium Deposition" and "Aluminium Sintering" steps. In Examples 2 and 3, in accordance with the invention the phosphorus doping was carried out after deposition and sintering of the aluminium layer. It can be seen that a sintering temperature of 950°C gave better results than one of 995°C.

TABLE 1

Example	Processing Conditions	Isc / A	Voc / V	Efficiency
1 (comparative)	POCl <sub>3</sub> doping at 960-1000°C + 0.5µm evaporated aluminium + sinter at 700°C	5.29	603	16.8%
2	0.5µm evaporated aluminium + sinter in O <sub>2</sub> at 950°C for 10 min + POCl <sub>3</sub> doping at 960-1000°C	5.48	611	17.9%
3	0.5µm evaporated aluminium + sinter in O <sub>2</sub> at 995°C for 30 min + POCl <sub>3</sub> doping at 960-1000°C	5.37	610	17.5%

Isc = short circuit current of cell under 1000 W/m<sup>2</sup> illumination with AM1.5G spectrum

Voc = open circuit voltage of cell under 1000 W/m<sup>2</sup> illumination with AM1.5G spectrum

Efficiency = electrical energy output over light energy input

#### 5 EXAMPLES 4 - 11

The process of Examples 2 and 3 was repeated using a variety of sintering temperatures and times. For comparison, a cell with a BSF applied according to the prior art process as in Example 1 above was also tested. The results are shown in Table 2. It can be seen that generally, lower sintering temperatures and shorter sintering times result in higher efficiencies.

TABLE 2

Example	Al sintering temp and time	No. of cells	Isc/A	Voc/V	FF(%)	Eff (%)
4	prior art process	26	5.18	604	77.1	16.4
5	995°C for 30 min	9	5.26	609	78.1	17.0
6	950°C for 50 min	9	5.22	607	78.5	16.9
7	950°C for 25 min	10	5.37	613	78.6	17.6
8	950°C for 10 min	10	5.42	615	78.7	17.8
9	900°C for 50 min	10	5.40	615	78.5	17.7
10	900°C for 25 min	10	5.41	616	78.4	17.7
11	900°C for 10 min	11	5.41	616	78.6	17.8

FF = Fill Factor, a measure of power out/(Isc\*Voc)

No. of cells is the number of cells tested to obtain the average values given in the Table

## CLAIMS

1. Process for incorporating a back surface field into a silicon solar cell, which comprises the steps of:
  - a) depositing a layer of aluminium on the rear surface of the cell;
  - b) sintering the aluminium layer at a temperature of between 700 and 1000°C;
  - 5 c) exposing the cell to an atmosphere of a compound of a Group V element, and diffusing at a temperature of between 950 and 1000°C, so as to dope exposed p-type silicon surfaces with said Group V element.
2. Process according to claim 1, wherein sintering temperature in step (b) is between 850 and 1000°C, preferably between 900 and 960°C.
- 10 3. Process according to claim 1 or 2, wherein the duration of the sintering in step (b) no more than 30 minutes, preferably no more than 10 minutes.
4. Process according to any preceding claim, wherein steps (b) and (c) are combined.
5. Process according to any preceding claim, wherein the Group V element is phosphorus or arsenic.
- 15 6. Process according to claim 5, wherein the compound of the Group V element is  $\text{POCl}_3$ .
7. Process according to any preceding claim, wherein doping of step c) is carried out at a temperature of between 960 and 1000°C.
8. Process according to any preceding claim, wherein the exposed p-type silicon
- 20 surfaces are in the grooves cut into the surface of the cell.
9. Process according to any preceding claim, wherein the silicon is monocrystalline.

**Fig. 1**